GRB941017: A Case Study of Neutrino Production in Gamma Ray Bursts

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ABSTRACT

GRB941017, a gamma-ray burst of exceptional fluence, has recently been shown to have a high-energy component which is not consistent with the standard fireball phenomenology. If this component is the result of photomeson interactions in the burst fireball, it provides new and compelling support for substantial high-energy neutrino fluxes from this and similar sources. In this letter, we consider what impact this new information has on the neutrino spectra of gamma-ray bursts and discuss how this new evidence impacts the prospects for detection of such events in next generation neutrino telescopes.

1. Introduction

Gamma-Ray Bursts (GRBs) are the most powerful objects in the universe, typically emitting luminosities between 10^{50} and 10^{54} erg/s over 0.1-100 seconds. Their energetics suggest that they may be the sources of the highest energy cosmic rays (Waxman 1995; Vietri 1995). It has been pointed out that, if high-energy cosmic rays are accelerated in GRBs, photomeson interactions between accelerated protons and target photons are inevitable, producing very high energy neutrinos and gamma-rays (see, for instance, Waxman & Bahcall 1997). Independent of any association of cosmic rays with GRBs, observable neutrino rates are predicted in models where similar energy goes into the acceleration of electrons and protons in the expanding fireball.

In October of 1994, the Burst And Transient Source Experiment (BATSE) and the Energetic Gamma-Ray Experiment Telescope (EGRET) each observed an exceptionally powerful example of such an object. GRB941017 has the eleventh highest fluence observed in the nine years of BATSE observations. More interesting, however, is the fact that this

burst displays not only the typical synchotron-inverse Compton spectrum at $\sim$30-1000 keV, but also shows a power-law high-energy component extending at least to 200 MeV in energy (González et al. 2003). Other than this burst, EGRET has seen four GRBs at energies of ~ 100 MeV. These were each consistent with an extension of the synchotron-inverse Compton spectrum (Dingus 2001). Additionally, Milagrito has also observed evidence for emission near ~ 100 GeV in one burst. This observation lacked the ability to reveal significant spectral information, however (Atkins et al. 2000). In a burst-by-burst analysis of the complete BATSE catalogue, Guetta et al. (2003) identified GRB941017 as the most powerful neutrino emitter with, unfortunately, no neutrino telescope to observe it in 1994. Although other explanations may be possible, GRB941017 provides the best evidence to date for high-energy proton interactions with source photons in GRBs.

If protons are accelerated to energies sufficient to produce the gamma-ray spectrum observed in GRB941017, high-energy neutrinos are a necessary consequence (Waxman & Bahcall 1997). Although no high-energy neutrino telescope of sufficient volume was operational in October 1994, it is interesting to consider the prospects for detection of a burst with similar characteristics in future experiments.

In this letter, we calculate the neutrino spectrum predicted for such an event, and discuss the prospects for detection in future experiments such as the kilometer scale neutrino telescope IceCube (Ahrens et al. 2003). Our conclusions are: i) An event like this is likely to be observable with $\sim 0.5 - 5$ events from a single burst and, ii) a handful of events of this type can produce the diffuse flux of order 10 events per year predicted by fireball phenomenology (Guetta et al. 2003).

2. Neutrinos From Photomeson Interactions In GRB Fireballs

Accelerated protons in GRB fireballs produce parent pions via the processes

$$p\gamma \rightarrow \Delta \rightarrow n\pi^+ \tag{1}$$

and,

$$p\gamma \rightarrow \Delta \rightarrow p\pi^0 \tag{2}$$

which have very large cross sections of $\sigma_\Delta \sim 5 \times 10^{-28}$ cm^2. The charged π's subsequently decay producing charged leptons and neutrinos, while the neutral π's decay into high-energy photons. To have sufficient center-of-mass energy for these processes to take place, protons must meet the threshold condition:

$$\varepsilon'_p \geq \frac{m_\Delta^2 - m_p^2}{4\varepsilon'_\gamma}. \tag{3}$$

Primed and unprimed quantities refer to values measured in the comoving and observer's frames, respectively. In the observer's frame,

$$\varepsilon_p \geq 1.4 \times 10^{16} \frac{\Gamma_{2.5}^2}{\varepsilon_{\gamma,\text{MeV}}} \text{eV}, \tag{4}$$

resulting in a neutrino energy

$$\varepsilon_\nu = \frac{1}{4}\langle x_{p\rightarrow\pi} \rangle \varepsilon_p \geq 7 \times 10^{14} \frac{\Gamma_{2.5}^2}{\varepsilon_{\gamma,\text{MeV}}} \text{eV}, \tag{5}$$

where $\Gamma_{2.5} = \Gamma/10^{2.5}$ is the bulk Lorentz factor and $\varepsilon_{\gamma,\text{MeV}} = \varepsilon_\gamma / 1\text{MeV}$ is the typical target photon energy. $\langle x_{p\rightarrow\pi} \rangle \simeq 0.2$ is the average fraction of energy transferred from the initial proton to the produced pion. The factor of 1/4 comes from the assumption that the 4 final state leptons in the decay chain $\pi^+ \rightarrow \nu_\mu\mu^+ \rightarrow \nu_\mu e^+ \nu_e \bar{\nu}_\mu$ equally share the pion energy.

Typical GRBs display a broken power-law spectrum consistent with synchotron and inverse Compton emission. This spectrum can be parameterized by:

$$F_\gamma = \varepsilon_\gamma dn_\gamma/d\varepsilon_\gamma \propto \begin{cases} \varepsilon_\gamma^{-\alpha}; & \varepsilon_\gamma < \varepsilon_\gamma^b \\ \varepsilon_\gamma^{-\beta}; & \varepsilon_\gamma > \varepsilon_\gamma^b \end{cases}. \tag{6}$$

In the case of GRB941017, α and β appear to change with time varying between 1.2 and 2.1 for β and between -0.2 and 0.5 for α. In the first tens of seconds of the burst, the break energy is about 500 keV. It steadily drops, falling well below 100 keV after about 100 seconds.

For each proton energy, the resulting neutrino spectrum traces the GRB photon spectrum, but with a much higher energy break:

$$\varepsilon_\nu^b = 7 \times 10^{14} \frac{1}{(1+z)^2} \frac{\Gamma_{2.5}^2}{\varepsilon_{\gamma,\mathrm{MeV}}^b} \mathrm{eV}. \tag{7}$$

z is the redshift of the GRB. For this particular burst, the redshift has been estimated to be $z \sim 0.6$, although its precise value is uncertain (Guetta et al. 2003).

At very high energies, pions lose energy by synchrotron emission before decaying. This affects the spectrum of neutrinos from pion decay above the energy:

$$\varepsilon_{\nu_\mu}^s = \frac{10^{17}}{1+z} L_{\gamma,52}^{-1/2} \Gamma_{2.5}^4 t_{v,-2} \quad \mathrm{eV}, \tag{8}$$

where $L_{\gamma,52}$ is the gamma-ray luminosity of the burst in units of 10^{52} erg/s. For GRB941017, $L_{\gamma,52} \simeq 1$. $t_{v,-2}$ is the time scale of fluctuations in the GRB lightcurve in units of 10^{-2} s Neutrinos from muon decay have an energy cutoff that is 10 times smaller due to the longer lifetime of the muon compared to that of the pion. Above this energy, the slope of the neutrino spectrum steepens by two.

The fraction of energy in accelerated protons converted to pions in the fireball is estimated from the ratio of the size of the shock, $\Delta R'$, and the proton mean free path:

$$f_\pi \simeq \frac{\Delta R'}{\lambda_{p\gamma}} \langle x_{p\to\pi} \rangle. \tag{9}$$

Here, the proton mean free path is given by $\lambda_{p\gamma} = 1/n_\gamma \sigma_\Delta$, where n_γ is the number density of photons. The photon number density is given by the ratio of the photon energy density

and the photon energy in the comoving frame:

$$n_\gamma = \frac{U'_\gamma}{\varepsilon'_\gamma} \simeq \left(\frac{L_\gamma t_v/\Gamma}{4\pi R^2 \Delta R'}\right)\Big/\left(\frac{\varepsilon_\gamma}{\Gamma}\right).$$

(10)

Using these equations, and the relationship $R \simeq 2\Gamma^2 c t_v$, it is found

$$n_\gamma \simeq \left(\frac{L_\gamma}{16\pi c^2 t_v \Gamma^5 \Delta R'}\right)\Big/\left(\frac{\varepsilon_\gamma}{\Gamma}\right) = \frac{L_\gamma}{16\pi c^2 t_v \Gamma^4 \Delta R' \varepsilon_\gamma},$$

(11)

which leads to

$$f_\pi \simeq \frac{L_\gamma}{\varepsilon_\gamma} \frac{1}{\Gamma^4 t_v} \frac{\sigma_\Delta \langle x_{p\to\pi} \rangle}{16\pi c^2} \sim 0.2 \times \frac{L_{\gamma,52}}{\Gamma_{2.5}^4 t_{v,-2} \varepsilon_{\gamma,\mathrm{MeV}}^b}.$$

(12)

Thus far, this calculation describes protons at the break energy. In general,

$$f_\pi(\varepsilon_p) \sim 0.2 \, \frac{L_{\gamma,52}}{\Gamma_{2.5}^4 t_{v,-2} \varepsilon_{\gamma,\mathrm{MeV}}^b} \times \begin{cases} (\varepsilon_p/\varepsilon_p^b)^\alpha & \varepsilon_p > \varepsilon_p^b \\ (\varepsilon_p/\varepsilon_p^b)^\beta & \varepsilon_p < \varepsilon_p^b \end{cases},$$

(13)

where ε_p^b is given by Eq.(4).

This equation indicates that f_π and, therefore, the spectrum's normalization and the final event rates, vary significantly from burst-to-burst (Halzen & Hooper 1999; Alvarez-Muñiz et al. 2000). Such fluctuations are constrained, however, and similar conclusions are reached when fixing $f_\pi = 0.2$, its typical value (Guetta et al. 2001).

To estimate the bulk Lorentz factor, Γ, we relate it to the peak energy of the gamma-ray spectrum:

$$\varepsilon_\gamma^b \approx \frac{L_{\gamma,52}^{-1/2}}{\Gamma_{2.5}^2 t_{v,-2}} \, \mathrm{MeV}.$$

(14)

For the case of GRB941017, we estimate $\Gamma \simeq 250$ and this is again somewhat uncertain (Guetta et al. 2003).

Finally, we obtain the neutrino spectrum:

$$\varepsilon_\nu^2 \frac{dN_\nu}{d\varepsilon_\nu} \simeq \frac{1}{8} \frac{F_\gamma}{\ln(10)} f_\pi$$

(15)

where, F_γ and f_π are determined by equations 6 and 13, respectively. The neutrino spectrum found for GRB941017 in the time bins in (González et al. 2003), is shown in figure 1.

3. Event Rates in Neutrino Telescopes

Currently, the AMANDA-II detector (Andres et al. 2001), located at the South Pole, provides the strongest limits for high-energy neutrinos from GRBs (Barouch & Hartdke 2001; Stamatikos et al. 2003). Considerably larger experiments such as the kilometer-scale neutrino observatory IceCube (Ahrens et al. 2003), are presently under construction. For a review of high-energy neutrino astronomy, see Halzen & Hooper 2002 or Learned & Mannheim 2000.

High-energy neutrinos are observed as muons or showers created in interactions inside or near a Cherenkov detector embedded in an optically transparent medium such as ice or water. Muons, created in charged current interactions travel several kilometers before losing the majority of their energy, thus enhancing their prospects for observation. The probability for observing an energetic muon is given by

$$P_{\nu_\mu \to \mu} = N_A R_\mu \sigma_{CC}, \tag{16}$$

where N_A is Avogadro's number, R_μ is the muon range (Dutta et al. 2001) and σ_{CC} is the neutrino-nucleon charged current cross section. For GRB941017, with a zenith angle of 94.5° (for experiments at the South Pole), there is sufficient ice to allow for very long muon ranges. In our calculations, we take into account the absorption of neutrinos in the Earth as well as the effect of oscillations.

All three flavors of neutrinos may interact producing showers within the detector volume. The probability of making such an observation is similar to the relation for muons,

although shower events do not benefit from long muon ranges, and typically they have to be produced inside the detector to be observed. More details on how the rate is calculated can be found, for instance, in Appendix C of Guetta et al. 2003.

The rates for a GRB similar to GRB941017 are shown in table 1. We have made two estimates of the rate. The first estimate uses Eq. 15 for the neutrino flux, obtaining F_γ from a broken power-law fit to the observed gamma-ray spectrum. It is important to remark that this fit cannot accommodate the late-time high-energy feature of the gamma-ray spectrum. We predict 0.3 events per square kilometer, or roughly 1 event in IceCube with an effective area for muons and showers exceeding $1\,\mathrm{km}^2$. Bear in mind that for an observation over a narrow temporal and angular window in coincidence with the optical display, the background is entirely negligible (Guetta et al. 2003). A single high-energy neutrino event is a conclusive observation. This rate is, of course, subject to the ambiguities associated with z and Γ.

To accommodate the late-time, high-energy feature seen in the gamma-ray spectrum, instead of using the method described above, we can, alternatively, estimate the neutrino flux and event rate by relating the observed high-energy gamma-ray component of GRB941017 to a corresponding high-energy neutrino component. This method assumes that the observed high-energy gamma-ray component is the result of photomeson interactions. The observed high-energy gamma-ray component of GRB941017 can be parameterized (González et al. 2003) by

$$\frac{dN_\gamma}{dE_\gamma} \simeq A_\gamma E_\gamma^{-\delta} \tag{17}$$

where δ is measured to be 0.96 to 1.10 (González et al. 2003) and A_γ is a normalization constant fixed to the observed spectrum. The corresponding neutrino flux can be calculated by energy conservation given that the physics of photomeson interactions fixes the ratio of energy going to photons and neutrinos (Alvarez-Muñiz & Halzen 2003). The

main uncertainties are the slope of the neutrino spectrum, and the energy to which the high-energy gamma-ray component extends. Without cascading of the gamma rays in the source both would be uniquely determined by the photon spectrum. This is not to be expected and we therefore calculate the neutrino flux varying the neutrino spectral slope and the high-energy cutoff of the gamma ray spectrum. Note that the latter is unobservable because high-energy gamma rays are absorbed on diffuse infrared background radiation.

The results are shown in figures 2 and 3. For a E^{-1} neutrino spectrum and a gamma-ray cutoff near 100 TeV, we predict ~ 10 events per square kilometer. Experiments capable of observing TeV gamma-rays from GRBs, such as MILAGRO (Atkins et al. 2001) and IceCube (Halzen & Hooper 2003) will be useful in determining the maximum energy to which the photomeson component of the gamma-ray spectrum extends.

Another way of summarizing our results is shown in figure 3 where the rate is plotted as a function of the neutrino spectral slope. The observed event rate increases with the spectral index because more neutrinos of lower energy are produced and, although their detection probability is smaller, their larger number compensates. This trend continues until a neutrino spectral slope of ~ 2.1. Above this slope, a significant amount of the energy goes into neutrinos below the experimental energy threshold of the detector and the rate decreases. The same argument explains why for a flatter neutrino spectrum, similar to the observed photon spectrum, the same event rate is reached for a higher gamma-ray cutoff as seen in figure 2.

Although $\sim 10^3$ GRBs are observed per year, the total rate from all of these events is typically estimated to be ~ 10 events per square kilometer per year (Guetta et al. 2003). A small number of exceptional bursts, such as the one we study here, can contribute substantially to the total neutrino flux.

4.   Conclusions

We have pointed out that the high-energy feature observed in GRB941017 provides further support for the expectation of detectable fluxes of high-energy neutrinos in coincidence with gamma ray bursts. We have estimated the neutrino spectrum that would accompany such a burst and discussed the prospects for such an event's detection in future neutrino observatories. We find that such an event is expected to produce on the order of 1 event in a kilometer scale neutrino telescope and that this would be a conclusive observation since there is no competing background during the time and in the direction of the burst.
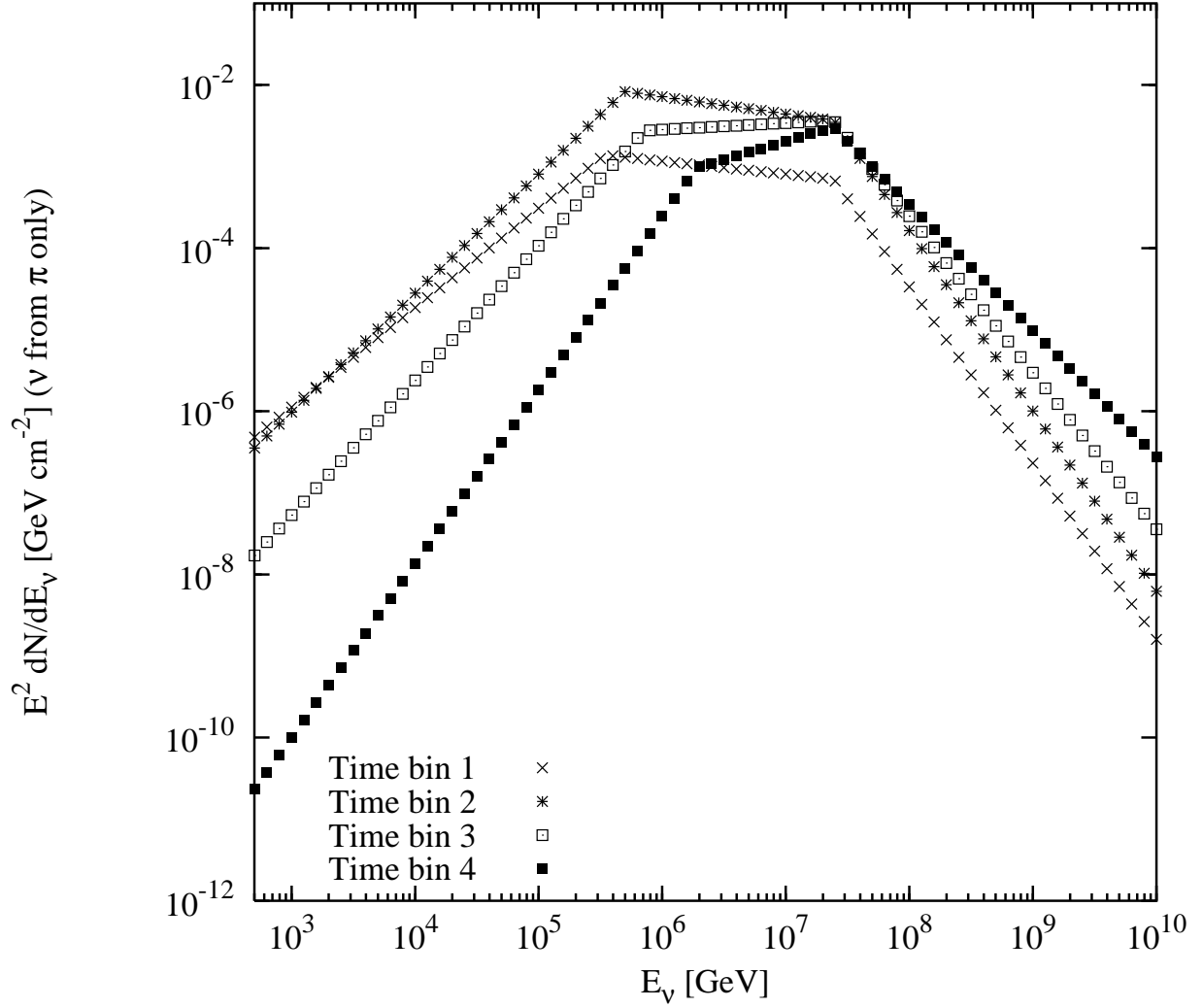
Fig. 1.— The high-energy neutrino spectrum estimated for GRB941017. The spectrum is shown for the four time bins in González et al. 2003, the first of which begins 18 seconds prior to the BATSE trigger time. Each bin is of ~33 second duration. In González et al. 2003, a fifth time bin is described which we find to have a negligible impact on the neutrino spectrum.
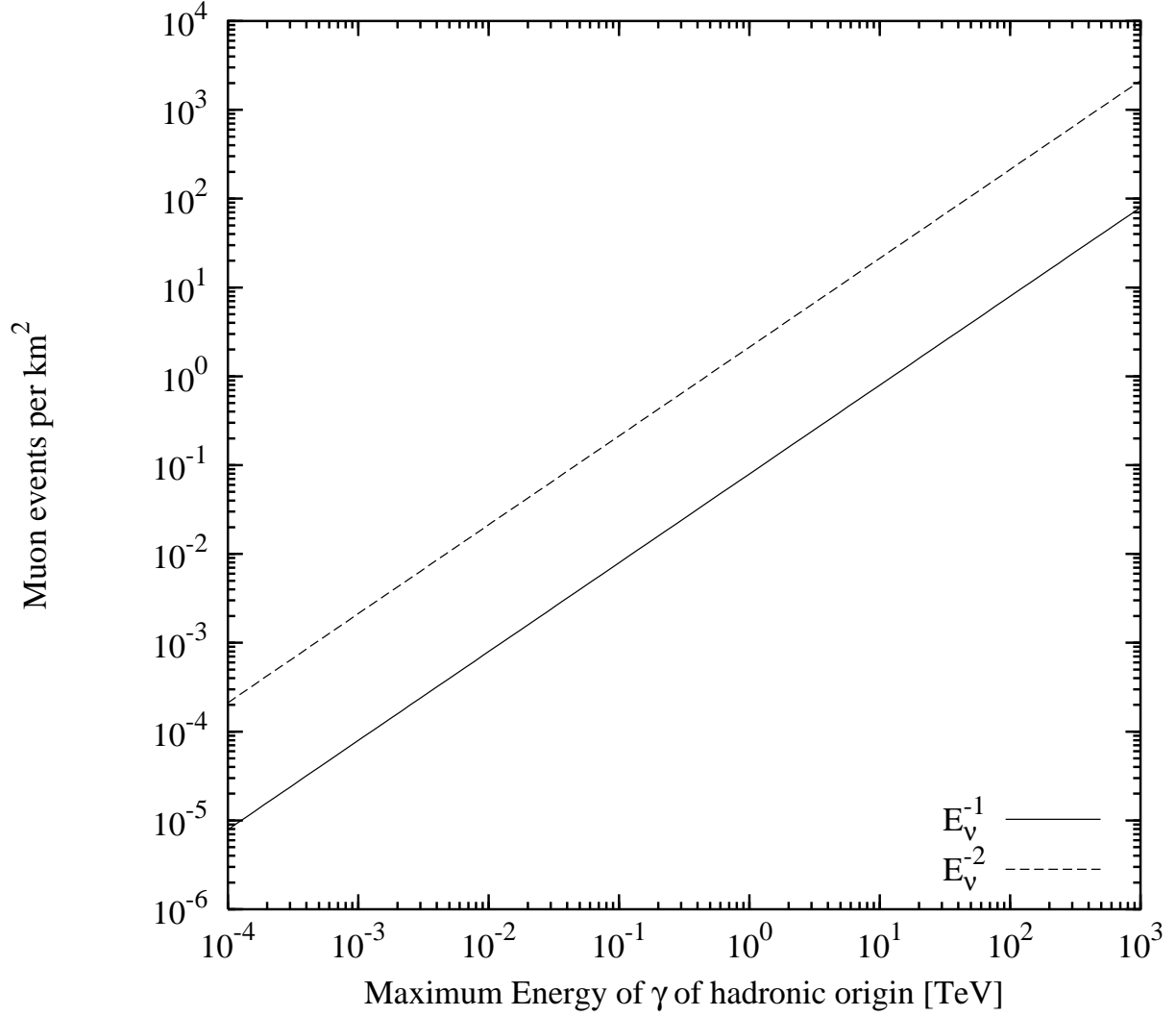
Fig. 2.— The muon neutrino event rate per square kilometer in a high-energy neutrino telescope for GRB941017 as a function of the energy to which the high-energy gamma-ray component observed by EGRET extends. The rate is calculated relating the observed high-energy gamma-ray component of GRB941017 to a corresponding high-energy neutrino component. Results are shown for two choices of accelerated neutrino spectra: E_ν^{-1} (solid line), E_ν^{-2} (dashed line). Protons are assumed to be accelerated up to $E = 10^{20}$ eV. The muon energy threshold is $E_\mu^{\text{thr}} = 100$ GeV.
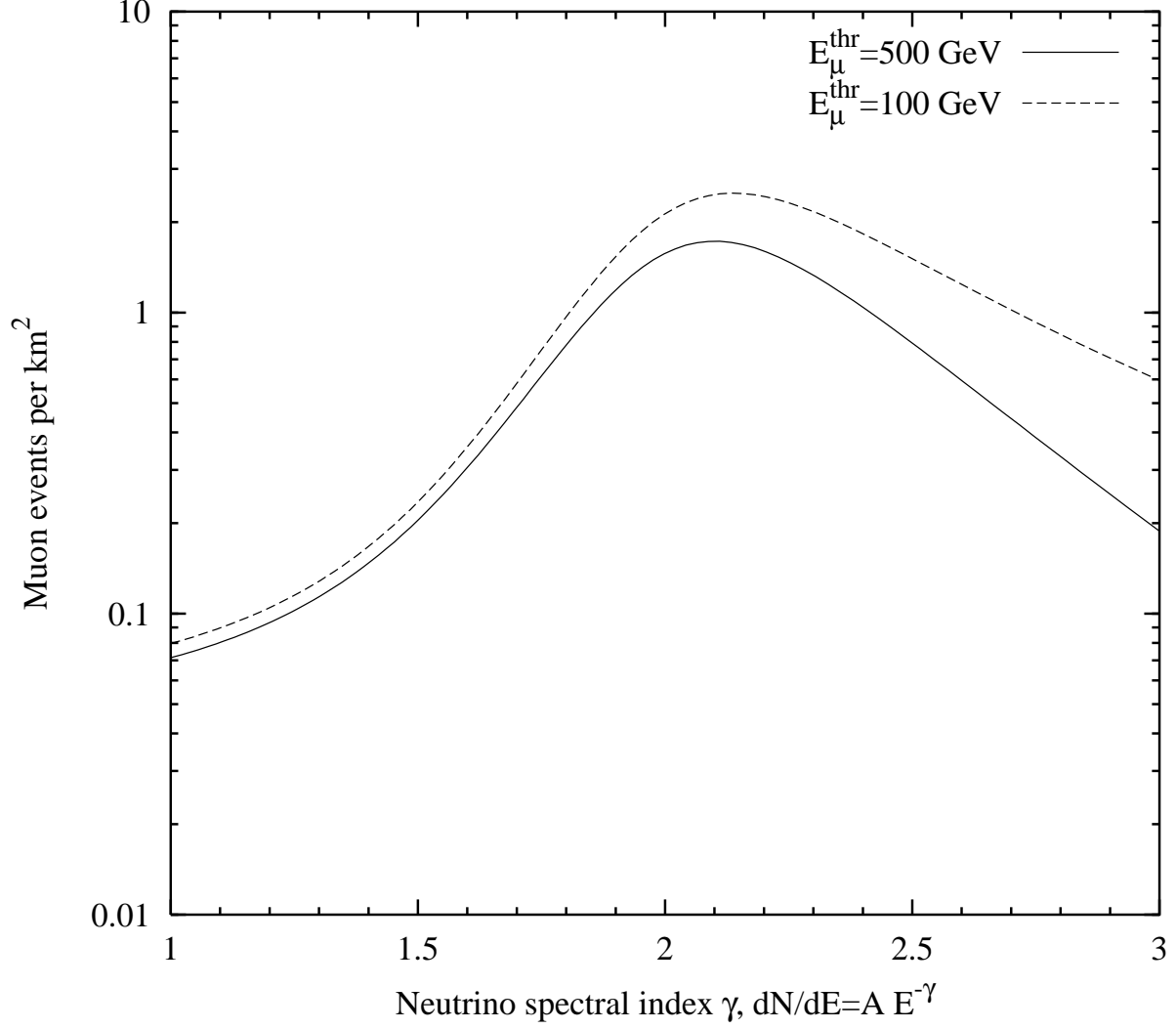
Fig. 3.— The muon neutrino event rate per square kilometer in a high-energy neutrino telescope for GRB941017 calculated by relating the total energy of gamma-rays in the high-energy component to the total energy in high-energy neutrinos. Results assume the high-energy gamma-ray component observed by EGRET extends to 1 TeV. Protons are assumed to be accelerated up to $E = 10^{20}$ eV. The effect of energy threshold is also shown: $E_\mu^{\rm thr}$=500 GeV (solid line); $E_\mu^{\rm thr}$=100 GeV (dashed line).

Calculation Method	Muons	Showers
Calculated From Target Density		
f_π Calculated	0.27	0.039
f_π Fixed (=0.2)	0.091	0.013
Inferred From Energy Conservation		
$E_\gamma^{\mathrm{max}} = 100\,\mathrm{GeV}$	0.21	0.065
$E_\gamma^{\mathrm{max}} = 1\,\mathrm{TeV}$	2.1	0.65
$E_\gamma^{\mathrm{max}} = 10\,\mathrm{TeV}$	21.	6.5

Table 1: The event rate (per square kilometer) from GRB941017 for two calculational methods. Those rates found by the target density calculation (as described in Section 2) are given for the calculated value of f_π the fraction of proton energy converted to pions, and for a fixed value of $f_\pi = 0.2$. This calculation assumes that roughly equal amounts of energy go into accelerating protons and electrons. The rates inferred from energy conservation are shown for three different choices of the maximum energy to which the high-energy gamma-ray component of the spectrum potentially extends. An E^{-2} proton injection spectrum is used. Both muon and shower energy thresholds are set to 100 GeV.

REFERENCES

Ahrens, J., *et al.* [IceCube Collaboration], 2003, to be published in Particle Astrophysics, astro-ph/0305196; http://icecube.wisc.edu/.

Alvarez-Muñiz, J., Halzen, F. & Hooper D. W., 2000, PRD, 62, 093015.

Alvarez-Muñiz, J., Halzen, F., 2003, ApJ 576:L33-36.

Andres, E. et al., 2001, Nature 410, 441.

Sokalski, I. et al. [ANTARES Collaboration], 2003, arXiv:astro-ph/0310130.

Atkins, R, *et al.* [Milagro Collaboration], 2000, ApJ 533 L119.

Atkins, R, *et al.* [Milagro Collaboration], 2001, arXiv:astro-ph/0110513.

Barouch, G & Hardtke, R., talk given at the International Cosmic Ray Conference, 2001.

Dedenko, L. G., Zheleznykh, I. M., Karaevsky, S. K., Mironovich, A. A., Svet, V. D. and Furduev, A. V., 1997, Bull. Russ. Acad. Sci. Phys. **61** 469 [Izv. Ross. Akad. Nauk. **61** 593].

Dermer, C. D., and Atoyan, A., 2003, arXiv:astro-ph/0301030

Dingus, B. L., 2001, in *High-Energy Gamma Ray Astronomy* (eds. Aharonian and Volk), 383, AIP, New York.

Dutta, S. I., Reno, M. H., Sarcevic, I. & Seckel, D., 2001, PRD, 63, 094020.

González, M.M. *et al.*, 2003, Nature 424, 749.

Guetta, D., Hooper, D., Alvarez-Muñiz, J., Halzen, F. and Reuveni, E., 2003, astro-ph/0302524, Astropart. Phys. in press.

Guetta D., Spada M., & Waxman E., 2001, ApJ 559, 101.

Halzen, F. & Hooper, D. W., 1999, ApJ 527, L93.

Halzen, F. & Hooper, D. W., 2002, Rept. Prog. Phys. 65, 1025.

Halzen, F., and Hooper, D., 2003, JCAP **0308**, 006

Learned, J. G. & Mannheim, K., 2000, Ann. Rev. Nucl. Part. Sci. 50, 679.

Stamatikos, M., 2003, Proceedings of the 2003 Gamma Ray Burst Symposium (AIP), Santa
        Fe, New Mexico.

Vietri, M., 1995, ApJ 453, 883.

Waxman, E., 1995, PRL, 75, 386.

Waxman, E., & Bahcall, J., 1997, PRL, 78, 2292.